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EXPERIMENTAL VERTIFICATION FOR APPLYING NEUTRAL EQUILIBRIUM MECHANISM AS MULTIPLE VIRTUAL PIERS OF DISASTER RELIEF BRIDGE

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The purpose of this research is to develop an active-control mechanism and its control law, to reduce the deformation of the relief bridge and weight of construction materials and improve the effective span of the bridge. The counter-force (control force) mechanism, provided by Neutral Equilibrium Mechanism, NEM, is applied to exert a counter-force at the selected position of the bridge and maintain the deflection at this selected position to be zero. This proposed NEM is used as a counter-force mechanism, which is an automatic control device consisting of a pair of pressed steel strands, rotary cantilever arm mechanisms, a displacement sensor and a controller to form as a virtual pier. In this study, these proposed counter-force mechanisms are installed at the positions of 1/3 and 2/3 span of the bridge: the effective span is only 1/3 of the original span, the maximum bending moment and maximum deflection is only 1/9 and 1/27 of the original bridge, respectively. The experimental results display that the ideal behavior of this NEM can be fully achieved in the dynamic moving load test. The deflection and the bending moment of the bridge at the position of installing these NEMs are near zero. The goals of reducing deformation and improving the carrying capacity of the bridge are realized.

Keywords: Deformation reduction, Reduced-scale bridge test, Dynamic test, Post-disaster rehabilitation.

1 INTRODUCTION

Recently, the effects of greenhouse gas have led to global warming and climate anomalies are becoming more and more obvious. Particularly, abnormal sea temperatures cause typhoons (hurricanes) to occur more frequently and typhoon intensity becomes stronger. If the geological conditions in the mountains are poor, coupled with the possibility of a collapse in mountainous areas after the earthquake or frequent landslides after typhoon season and heavy rains. To carry out immediate disaster relief and post-disaster rehabilitation, the disaster relief unit must rely on the bridge with the function of life for ground transportation. Unfortunately, the damage to the bridge after the disaster is impassable, seriously affecting the relevant disaster relief and rehabilitation work. Therefore, a temporary disaster relief bridge must be assembled quickly for relief efforts. To process post-disaster rehabilitation quickly, our research team is developing a new type of relief bridge. That is, the neutral equilibrium mechanism (NEM) being developed is used as the virtual pier of the bridge to act as a solid pier and diminish the vertical displacement of the bridge caused by the dynamic load such as rescue vehicles. The internal stress state of the bridge can be actively adjusted through NEM's internal control mechanism. The control force of a single NEM can be changed according to the vertical displacement of the continuous structure supporting dynamic loads (Shih *et al*. 2018). The disaster relief bridge can be installed with more NEMs at the suitable locations of the bridge to form as a multi-virtual pier of the bridge. The net span and applicability of this kind of bridge can be expanded. The active counter-force mechanism of NEM relates to the prestressed steel strands as the counter-force point. The active control force changes with the perpendicular direction displacement of bridge, caused by dynamic load. Thus, the perpendicular direction displacement and the bending moment of the bridge at the installed place of the bridge with NEM is almost unchanged. Relevant research achievements (Shih *et al*. 2018, Shih and Sung 2019a, Shih and Sung 2019b, Sung and Shih 2019, Shih and Sung 2019c) have been verified the applicability and the control effect of this proposed method. To test and verify the control effect of the bridge with multi-virtual pier, this test bridge is installed at the one-third and two-thirds places of this reduced scale bridge with two NEMs, tested by dynamic test.

2 MODEL OF APPLYING NEM AS MULTIPLE VIRTUAL PIERS

Neutral Equilibrium Mechanism, applied to form as virtual pier, is composed of cantilever mechanism with servo, steel strands, microcontroller unit and anchor seats. The control force for the cantilever mechanism can be provided by the prestressed steel strands, fixed by the anchor seats in fixed positions. Microcontroller unit (MCU) is an integrated circuit with CPU, built-in flash memory, digital I/O ports and analog I/O ports. It is programmable and can work independently. So it can realize the miniaturization of the hardware. The role of the microcontroller is to acquire the responses of the structure to be controlled, then calculate the required rotation angle of the cantilever arms according to the preset PID controller, and then transmit the control signal to the servos. The above actions should be performed continuously at a frequency not less than 500 Hz.

NEM provides the control force, is produced by the cantilever arms, prestressed with steel strands. If the prestressed steel strands are T, the bridge span is L, and the length of cantilever arm is l, the steel anchor and steel strands angles can be acquired as seen in Eq. (1):

$$\theta = \tan^{-1}\left(\frac{2l}{L}\right) \tag{1}$$

Then the resultant force R can be gotten from θ as seen in Eq. (2):

$$\mathrm{R} = 2T \cdot \sin\theta \tag{2}$$

The magnitude of the vertical component of the resultant force R depends on the depression angle φ of the cantilever. Since each NEM consists of two cantilever mechanisms that rotate symmetrically to each other, the horizontal components of R cancel each other out, and the total vertical component, defined as the control force u, can be expressed as seen in Eq. (3):

$$u = 4T \cdot \sin\theta \cdot \sin\varphi \tag{3}$$

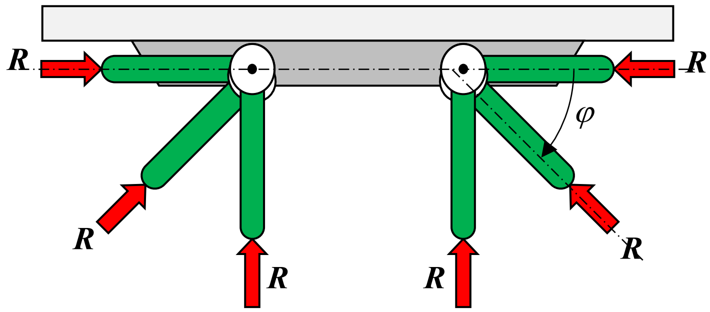

Figure 1. Front View of NEW and angle variation.

3 TEST SET-UP AND TEST PARAMETERS

To explore the control effect of two NEMs for the bridge as two virtual piers, the reduced-scale bridge, subjected to self-weight and service load, is designed to test and verify the displacement and the bending moment control effects. This test is also to verify the stability and workability of this proposed NEM to take shape as a multiple-virtual pier of the bridge. The request materials and test specifications of this bridge are listed in Table 1. The overall reduced-scale bridge with the test scheme is shown in Figure 2.

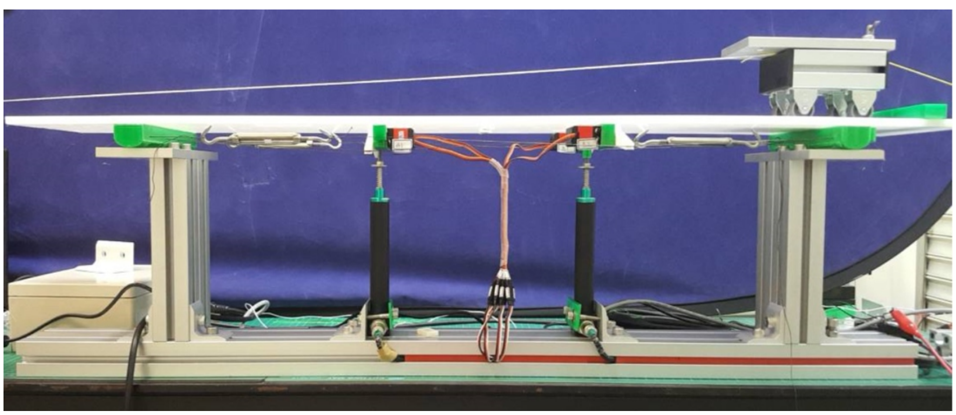

Figure 2. The overall test scheme of reduced-scale bridge with two NEMs.

The experimental sensor part: (1) displacement meters are applied to measure the displacement responses of the bridge, subjected to dynamic load at the one-third position and two-thirds position of this test bridge; (2) the displacements and time interval of the sensor data of MCU are detected by microcontroller unit, MCUs to calculate the speed responses of the bridge. The operating principle is to receive the displacements change at the one-third position and two-thirds position of this test bridge from the displacement meters and calculate their instantaneous velocity, respectively. Then, the required control forces are separately calculated to predict the rotation angles of these two positions by eq. (3) of Radio Control Servos to turn the Radio Control Servo to their suitable angles to provide the appropriate control forces. The Radio Control Servo for the remote-control model is only required very little output power to investigate the displacement responses of the bridge with two NEMs under excitation of dynamic load. The control effect comparison of the bridge without NEM and with two NEMs, installed with a PID controller with one control gain under dynamic load, is tested in this research. Table 1 is maddening a list of the experimental parameters of this test in Table 1.

Table 1. Test materials, specification, and test parameters of reduced-scale bridge.

Classification	Material	Design Specification	Quantity
Control mechanism	Radio Control Servo	Torque size: 250N．cm; Control accuracy of Radio Control Servo angle: 1.2 degree	4
	Cantilever arm	Length between the link of fixed steel strand and anchor point: 50mm; Test material: Polylactide (PLA), madden by 3D printing.	4
	Polyethylene Line (PE)	Tensile strength: 250N	2
Model of Bridge	Bridge Deck	Dimension: Length=1100mm, width= 120mm, thickness=15mm, moment of inertia of area=2 x 10^5(mm^4); Material of bridge deck: Polypropylene plastic sheet, polypropylene (PP); Young's modulus is between 1300~1800(N/mm^2).	2
	Anchor seat	Dimension: Length=120mm, width=30mm, thickness=20mm; Material: Aluminum alloy metal block; Support form: Simple support.	4
Sensor	Displacement meter	Resistive type	2
Controller	Microcontroller unit (MCU)	Arduino nano V3	2

Test parameter	Parameter range
Dynamic test	Self-weight: 18.97N; Vehicle speed: 6.38 cm/sec, Test vehicle speed is equivalent to 4.5km/hr.
	Without installation NEM control Installation with two NEMs with control gain of PID controller: G_P=2, G_D=0.0 G_I= 0.02

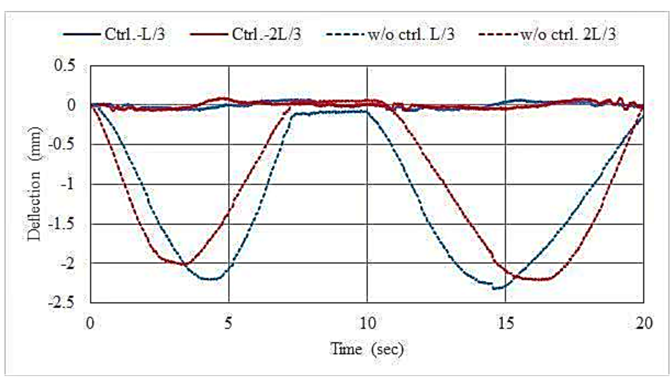

Figure 3. The time history of perpendicular direction displacement responses of bridge without controlled and with two NEMs controlled.

4 TEST RESULTS AND DISCUSSIONS

The test results are shown in Figure 3. The vehicle goes back and forth twice during this experiment. The 0~7.5 seconds are the go forth of moving load, the 7.5~10 seconds is the waiting time for the vehicle to reverse from the end of the bridge and the 10~20 seconds are the back of moving load. The red and blue dotted lines are shown the time history of displacement responses at the one-third position and two-thirds position of the bridge without control under the excitation of dynamic load, respectively. The red and blue solid lines are displayed for those at the one-third position and two-thirds position of the bridge with NEMs controlled, respectively.

The control mechanism of the test bridge with two NEMs, installed at the one-third position and two-thirds position of the bridge is described as follows, one to five stages for the go forth responses and six to nine stages for back responses, respectively:

(1) Phase 1: The cantilever arms of NEMs at the one-third position and two-thirds position of the bridge maintain a horizontal balance, and there is no perpendicular displacement of the bridge.

(2) Phase 2: When the dynamic load is moving to the position between the beginning and 1/3 position of the test bridge, the perpendicular displacement of the bridge without the NEMs controlled is 1.5 mm and 1 mm at 1/3 position and 2/3 position of the bridge, respectively. The perpendicular displacement is only 0.05 and 0.04 mm at 1/3 position and 2/3 position of bridge with NEMs controlled, respectively. The rotation angle of the Radio Control servo at 1/3 position of the bridge turns lager than that at 2/3 position of the bridge.

(3) Phase 3: When the dynamic load is located at the midpoint of the bridge, the perpendicular displacement of the bridge without the NEMs controlled is 1.8 mm and 2.2 mm at 1/3 position and 2/3 position of the bridge, respectively. With the NEMs controlled, both rotation angles of the Radio Control servos increase, and the perpendicular displacements are raised only 0.04 and 0.05 mm at 1/3 position and 2/3 position of the bridge, respectively.

(4) Phase 4: When the dynamic load is moved to the position of 2/3 point and the end of the bridge, the perpendicular displacements without the NEM controlled are 0.9 mm and 1.5 mm at 1/3 and 2/3 of the bridge, respectively. With the NEMs controlled, the rotation angle of the Radio Control servo at 1/3 of bridge turns fewer degrees than that at 2/3 of bridge. The perpendicular displacement only goes up 0.03 and 0.02 mm at 1/3 and 2/3 of the bridge, respectively.

(5) Phase 5: The bridge bears only the dead load of the bridge. The rotation angles of the NEMs return to the horizontal direction and there is no perpendicular displacement.

(6) Phrase 6: When the dynamic load is moving back to the 2/3 point and the bridge end, the perpendicular displacements of the bridge without the NEM controlled are 1.0 mm and 1.5 mm at 1/3 position and 2/3 position of the bridge, respectively. With the NEMs controlled, the rotation angle of the Radio Control servo at 1/3 of the bridge turns less degrees than that at 2/3 of the bridge. The perpendicular displacement is only 0.02 and 0.01 mm at 1/3 and 2/3 of the bridge, respectively.

(7) Phase 7: When the dynamic load is moving to the midpoint of the bridge, the perpendicular displacement of the bridge without the NEMs controlled is 2.1 mm and 2.3 mm at 1/3 and 2/3 of the bridge, respectively. With the NEMs controlled, the perpendicular displacements are decreased to -0.01 and 0.01 mm at 1/3 position and 2/3 position of the bridge, respectively.

(8) Phase 8: When the dynamic load is moving back to the 1/3 and beginning point of the bridge, the perpendicular displacement of the bridge without the NEMs controlled is 1.5 mm and 1.1 mm at 1/3 position and 2/3 position of the bridge respectively. With the NEMs controlled, the perpendicular displacement is dropped to 0.01 and -0.01 mm at 1/3 and 2/3 of the bridge, respectively. Otherwise, the rotation angle of the Radio Control servo at 1/3 position of the bridge turns lager degrees than that at 2/3 position of bridge.
(9) Phase 9: All responses are the same as those of Phase 1.

Comprehensive experimental results can be expressed as follows:

(1) The rotation angle of NEMs can be rotated to suitable angles and provide adequate counter-force to decrease the perpendicular displacement of the bridge by the dynamic load.
(2) The time history of displacement variation at the 1/3 and 2/3 of the bridge with the NEMs controlled display that the maximum perpendicular displacements are dominated to far below 1/400 of the net span of the bridge, required by the design criteria of the bridge.
(3) The displacements and bending moments of the bridge under control of NEMs at the installed positions of the bridge are near zero. The displacement reductions of the bridge at the installed NEMs positions are greater than 95%.

5 CONCLUSIONS

Multiple NEMs are applied to form as multi-virtual piers of the bridge are tested and verified in this research. These developed NEMs are installed at 1/3 and 2/3 of the bridge; then, the dynamic test is to explore the control effect of the bridge with multi-virtual piers. This research verifies that the practicality of employing multiple NEMs to constitute as multi-virtual piers that the perpendicular displacements and bending moment of the bridge can be controlled effectively.

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